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Abstract

A pseudotachylyte bounded by a carbonate-matrix implosion breccia was found at a fossilized out-of-sequence thrust in the Shimanto accretionary complex, Japan. This occurrence resulted from the following events: first implosion of host rock due to interstitial fluid pressure increase and asymmetric fracturing; second, Ca-Fe-Mg carbonate precipitation; and third, frictional melting. The rock-record suggests that these events took place in a single seismogenic slip event. Resulting from abrupt drop in fluid pressure after implosion, hydro-fracturing and fluid escape, recovered high effective friction promoted melting during fault movement. Coexistence of fluid implosion breccia and pseudotachylyte has never been reported from continental pseudotachylyte, but might be characteristic from hydrous seismogenic faults in subduction zone.

1 Introduction

Pseudotachylyte formed by frictional melting has been the only convincing geologic evidence of rapid slip along seismogenic faults (e.g. Spray, 1992; Cowan, 1999). Under hydrous conditions, however, frictional melting has been considered to be prevented and other mechanisms, such as thermal pressurization of pore fluid (Sibson, 1973, 1975; Lachenbruch, 1980; Mase and Smith, 1987), acoustic fluidization (Melosh, 1996; Otsuki et al., 2003), or elastohydrodynamic lubrication (Brodsky and Kanamori, 2001), were thought to contribute to the dynamic weakening for unstable slip of earthquakes. In the seismogenic subduction zone, therefore, the predominant mechanisms have been implicitly considered to be fluid-induced weakening without frictional melting because the subduction zone is fundamentally rich in water under relatively low temperature conditions.

Recently geological evidence of frictional melting has been increasingly reported from several ancient accretionary prisms uplifted from seismogenic depths of subduction zones (Ikesawa et al., 2003; Austrheim and Andersen, 2004; Rowe et al., 2005; Kitamura et al., 2005) but the relationship between the conflicting mechanisms; e.g. thermal pressurization of fluid and frictional melting is still unclear.

We found a new exposure of pseudotachylyte from a fossilized out-of-sequence thrust (OOST) in an exposed accretionary prism. This is a unique fault, not previously reported, is associated with an implosion breccia embedded in a precipitated carbonate matrix, suggesting that both thermal pressurization of fluid/hydrofracturing (Sibson, 1986) and frictional melting operated. In this paper, we first describe the fault rock and then discuss dynamic weakening process in the hydrous seismogenic fault.

2 Geologic setting

The Nobeoka thrust is an OOST bounding the northern and southern Shimanto Belts of the Cretaceous-Tertiary accretionary complex in Kyushu, southwest Japan (Fig. 1). The thrust is traceable for more than 300 km in the Shimanto Belt, parallel to the modern Nankai Trough.

Hanging-wall rocks of the thrust are composed of the Eocene Kitagawa Group of plastically deformed meta-shales and meta-sandstones. Foot-wall strata of the Eocene Hyuga Group are composed of shale matrix mélange with sandstone and basaltic blocks deformed mainly by a brittle mechanism. The deformation fabrics of these rocks are consistent with the sense of shear along the Nobeoka Thrust (Kondo et al., 2005). Geo-thermometry using vitrinite reflectance indicates that the Kitagawa and the Hyuga Groups experienced heating up to maximum temperatures of about 320° and about 250°, respectively (Kondo et al., 2005). The Nobeoka thrust is characterized by a cataclastic fault core about 20 cm thick and by a brittle damage zone whose thickness is several tens of meters in the hanging-wall and about 100 meters in the foot-wall. Ubiquitous subsidiary shears, whose orientation is parallel to that of the fault core of the Nobeoka thrust, are present in the damaged zone.

Kondo et al. (2005) pointed out that the Nobeoka Thrust was formed at seismogenic depths from the viewpoint of thermal models (e.g., Hyndman et al., 1997), in comparison with the OOST in the modern Nankai Trough (Park et al., 2002) and on the basis of cataclastic deformation with fluid flow although direct evidence such as pseudotachylyte was not documented.

3 Asymmetric crack, implosion breccia and pseudotachylyte

A unique fault rock was found from one of the subsidiary faults in the hanging wall about 10 m above the fault core of the Nobeoka thrust. The subsidiary fault is composed of two different parts along the fault surface: narrow, planar slip sections and wider zones along dilation jogs (Fig. 2A). The planar slip section shows two-stages of deformation, first by asymmetric extensional cracking, especially in the foot-wall, then by frictional melting. The dilation jogs apparently deformed by a single stage of implosion.

3.1 Implosion breccia of the boundary of the fault core, dilation jog and asymmetric extensional cracks

Fault core of the slip sections is bounded mainly by host rocks but partly by a cataclasite-like zone (Fig. 2D). The zone is bounded by a clear wavy wall from the host in the hanging wall and connected with cracks in the foot-wall (Figs. 2A, B).

The cataclasite-like zone is composed of breccias of the host rock made of grains of various size embedded in a dark matrix. EPMA (Electron Probe Micro-Analyzer) and XRD (X-ray Diffractometer) analyses evidence that the matrix is made of precipitated Ca-Fe-Mg carbonates that are not found in the host rocks.

The breccia is also present in cracks in the foot-wall and the dilation jogs (Figs. 2A–D). The shapes of the cracks are irregular, but orientations ~30–40° clockwise from the slip plane dominate. Fewer cracks are orientated parallel to the foliation of the host rocks (Figs. 2A, F). Thicknesses of the veins decrease with distance from the fault core (Fig. 2A, B). The lengths of the jogs are several tens of cm parallel to the slip direction (Fig. 2A), which is indicative of displacement along the fault.

The dilation jogs are filled by Ca-Fe-Mg carbonates that encircle breccias of host rocks (Figs. 2A, D). The component is similar to that of the implosion breccia observed in the slip part as described. Crystal sizes of carbonates are smaller than a few tens of μm (Fig. 4B).

3.2 Pseudotachylyte

A mm thick fault core along the slip part of the fault is composed mainly of materials that are translucent under the optical microscope (Fig. 2E). Chemical analysis by EPMA (Fig. 3A), crystallographic analysis by XRD (Fig. 3B) and TEM (Transmission Electron Micrograph) analysis (Fig. 4H) revealed that the pseudotachylyte is now composed dominantly of palygroskite ($Al_2Fe\square_2Si_8O_{20}(OH)_2(OH_2)_4Mg(H_2O)_4$) and amorphous materials. Survival fragments are quartz, calcite and illite-chlorite aggregates. Palygorskite is never found in the host rocks (Fig. 3B).

SEM-BSI (Scanning Electron Microscope- Back Scatter Image) enabled the observation of various melt-and-quench related features of pseudotachylyte. The pseudotachylyte constitutes the "upper and lower domains" in Fig. 4A. The "upper domain" is composed of homogeneous matrix containing a few fragments of quartz, calcite and illite-chlorite aggregates. Margins of the fragments are plastically deformed and show embayment and frame texture due to melting erosion (Figs. 4D and E). Fe-rich micro-spherules with diameter of several μm are distributed along the hanging-wall of the upper domain (Figs. 4C and H). The size of the spherules becomes larger as the upper margin is approached (Fig. 4C). Their crystallization might have resulted from oxidation of Fe in melt during the melt-quenching event (Nakamura et al., 2002).

Elongated voids at a scale of a few to several μm are recognized in the upper domain (Fig. 4F). Elongated voids show internal tiny vesicles and globular material surfaces (Fig. 4G) similar to features described by Kennedy and Spray (1992). Stretched icicle-like features are observed within the cracks (Fig. 4H). Cooling cracks enveloping partially molten grains are also well displayed (Fig. 4D).

The lower domain consists dominantly of ultracataclasitic aggregates (Fig. 4A). Margins of fragments mostly retain their original shapes although melting initiation is observed, especially in the illite/chlorite aggregates. Larger fragments are concentrated in the upper part of the lower domain and floated in the upper molten domain (Fig. 4A). Such aspects resemble grain flow textures of sediments.

The pseudotachylyte, especially the completely molten upper domain, pinchs out as the dilation jog filled by implosion breccia is approached (Figs. 2A, D).

4 Discussion

Here we discuss the characteristic aspects of the fault described above and its significance for the seismogenic fault.

4.1 A single slip fault

The two staged deformation in the slip part show that fracturing with fluid implosion occurred first, followed by frictional melting. One explanation is a long hiatus between the two events and accidental slip along the same fracture. If this was the case, slip repetition should be recorded in the fault core (e.g., layered pseudotachylyte; Otsuki et al., 2003) and part of the dilation jog should be cut by the fault. The internal texture of pseudotachylyte, however, does not represent such a repetition, but rather represents a simple separation of upper and lower domains as described. The separation appears to be a gravitational effect because inverse grading texture of fragments resembles grain flow textures common in sediments. Thus, the fluid implosion with fracturing might have occurred early, with the frictional melting occurring later during a single slip event. The planar part fades into the dilation jog that is filled only by implosion breccia. This occurrence suggests that the fracturing was concentrated at the jog during slip propagation. Thus, the observed fault suggests a single slip event with several tens of cm displacement.

4.2 Asymmetric cracking with implosion breccia

Theoretically predicted cracking in the "process and damage" zones (Cowie and Scholz, 1992; Scholz et al., 1993) is observed in many natural examples (e.g. Vermilye and Scholz, 1998; Kim et al., 2004). They show that extensional Mode I fractures develop in parallel to the transient $\sigma 1$ in the vicinity of the fault tip, and/or around jogs, which progress to the damaged zone as a result of slip propagation (e.g. Kim et al., 2004). Asymmetric development, the angle between crack and fault surface, and the change in crack-width that we observed are quite consistent with those of the Mode I fractures in the damage zone (Kim et al., 2004).

A difference from commonly observed Mode I fractures is that the cracks are filled with carbonate and connected with the dilatant jog. Such an occurrence suggests that the Mode I rupture is not only due to transient stress concentration around the fault propagating tip or jog but also due to hydro-fracturing, that would have taken place due to a large fluid pressure gradient between the pore fluid in preceding cracks in the process zone or jog, and the damage zone (Billi et al., 2003). Such a large pressure difference between the source and sink collapses the wall and produces the implosion breccia (Sibson, 1986).

4.3 Ca-Fe-Mg carbonate precipitation for the matrix of implosion breccia

Crack-filling veins and matrices of implosion breccia are characteristically composed of Ca-Fe-Mg carbonates as described. The matrix-supported texture suggests rapid precipitation of carbonates because, if precipitation did not occur quickly, the grain structure would have collapsed, leading to a grain-supported structure. The mean diameter of matrix carbonate crystals is less than a few tens of μm. Such tiny crystal aggregates are different from ordinary vein-filling carbonates and suggestive of abrupt precipitation, although the exact time scale is unknown.

Carbonate solubility is controlled by Ph, KH and CO_2 concentration of the fluid, which depend on pressure-temperature conditions (Holland, 1967; Holland and Ma-

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linin, 1979). Dynamic formation of extensional cracks and jogs results in adiabatic fluid expansion and sudden fluid pressure drop, which abruptly reduces the solubility of carbonates and would precipitate tiny crystals.

4.4 Fluid thermal pressurization to abrupt depressurization, and friction recovery to fusion melting

Friction in the beginning stage of slip easily raises the temperature along the slip plane. In this state, the interstitial fluid of the fault zone surrounded by impermeable host rock is thermally pressurized and attains lithostatic fluid pressure (Sibson, 1973; Lachenbruch, 1980; Mase and Smith, 1987; Rice, 2005; Melosh, 1996). Only a few mm to cm slip is enough to supply the energy for the thermal pressurization (Sibson, 1973; Lanchenbruch, 1980; Mase and Smith, 1987; Rice, 2005). If the lithostatic pressure is maintained, there is no effective shear strength on the slip plane which is lubricated. However, if the thermally raising fluid pressure exceeds the effective tensile strength, the pressure triggers the hydro-fracturing and implosion (e.g. Sibson, 1973, 1975). Such abrupt extensional fracturing suddenly drops the fluid pressure. The rapid decrease of the fluid pressure means that effective shear strength is recovered and shear heating goes again to fusion melting at the slip plane. Recovered friction might raise again the temperature and pressure of interstitial fluid in the damage zone and might enhance the fluid flow into the dilatant jog. Rock records observed in this study suggests such a dynamic feedback may occur in the stage of slip propagation of seismogenic faulting in a subduction zone, although quantitative temperature and pressure estimation due to thermal pressurization and its associated time-scale is a challenge for the future.

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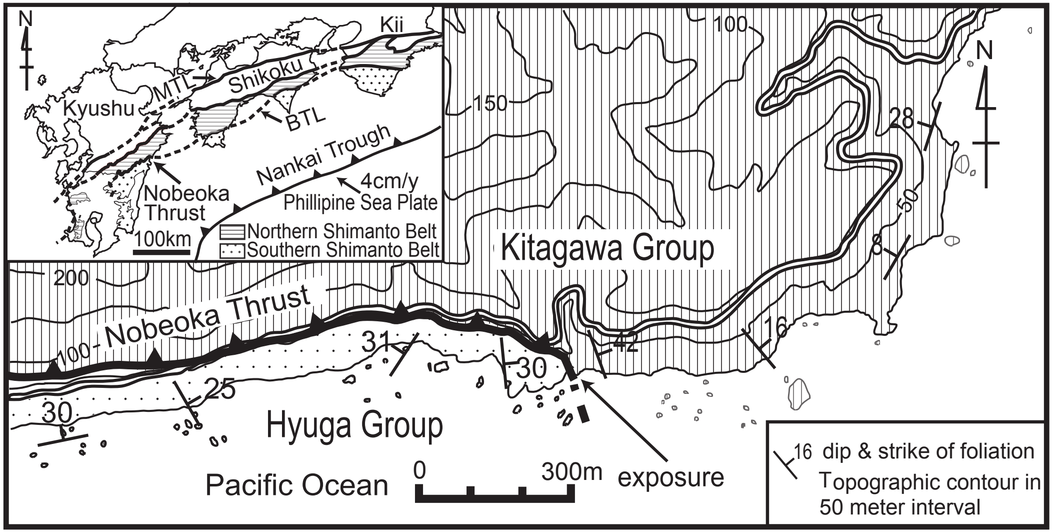

Fig. 1. Location map of the Nobeoka thrust and exposure of the studied fault.

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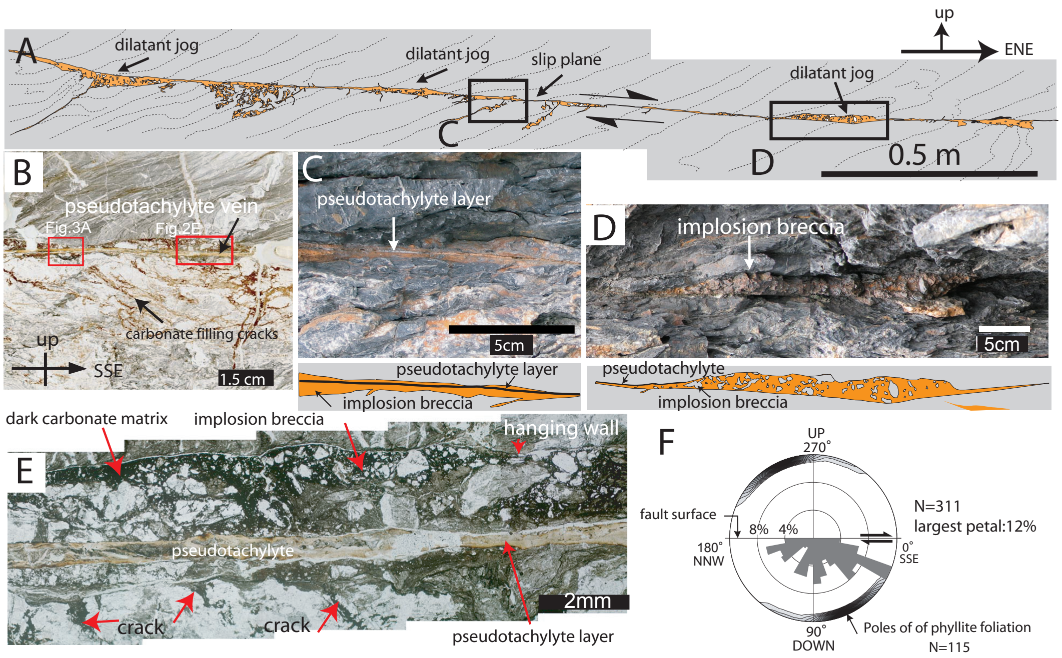

Fig. 2. Sketch and photographs of the studied fault. **(A)** sketch of the fault. Outcrops are oblique to the slip direction (SSE). Note that the fault is composed of two parts: sharp planar sections and dilation jogs. **(B)** and **(C)** Outcrop of slipped part. **(D)** Outcrop of dilatant jog. **(E)** Photomicrograph of the slipped part. Note that translucent fault core is bounded by cataclasite-like breccia in the dark carbonate matrix. **(F)** Orientation frequency diagram of cracks filled by carbonate together with lower-hemisphere stereograph of foliations. The orientation is measured on thin sections in parallel to the slip direction and perpendicular to the fault plane, foliations of host-rock phyllite and the cracks. Note that predominant orientations are 30°~40° clockwise from the slipped plane. Other large cracks are controlled by foliation as shown in (A).

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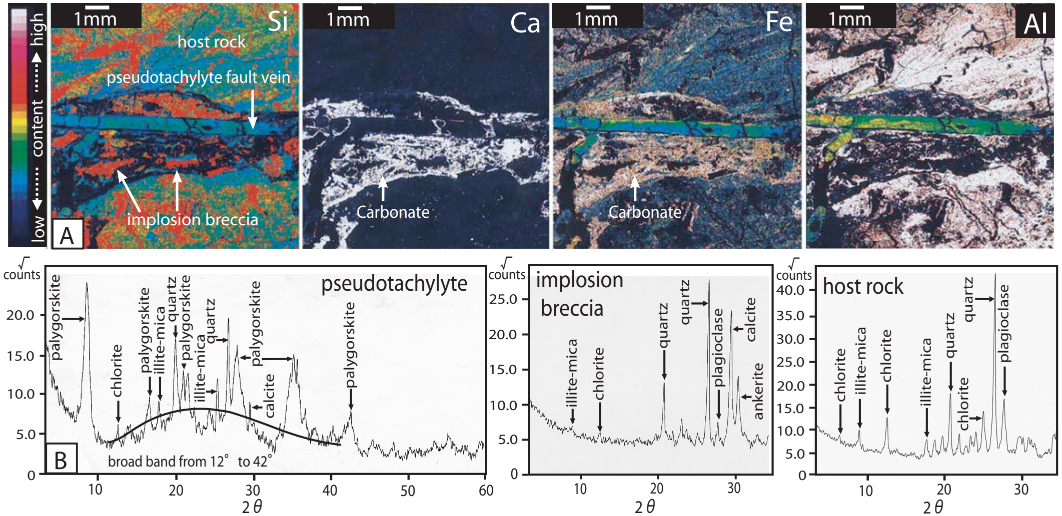

Fig. 3. (A) EPMA elements mapping of the pseudotachylyte, implosion breccia, and host rock. Note that Si, Fe, Mg and Al characterize the pseudotachylyte. Fe, Mg and Ca are found from the matrix of implosion breccia. Location for these maps is shown in Fig. 2E. **(B)** XRD analyses for the pseudotachylyte, implosion breccia, and host rock. Note the broad band ranging from 12° to 42° of the pseudotachylyte, which coincides with that of glassy material reported by (Lin and Shimamoto, 1998). Palygorskite and the broad band never presents in parts of implosion breccia and host rock, and calcite and ankerite are not found in the host rocks.

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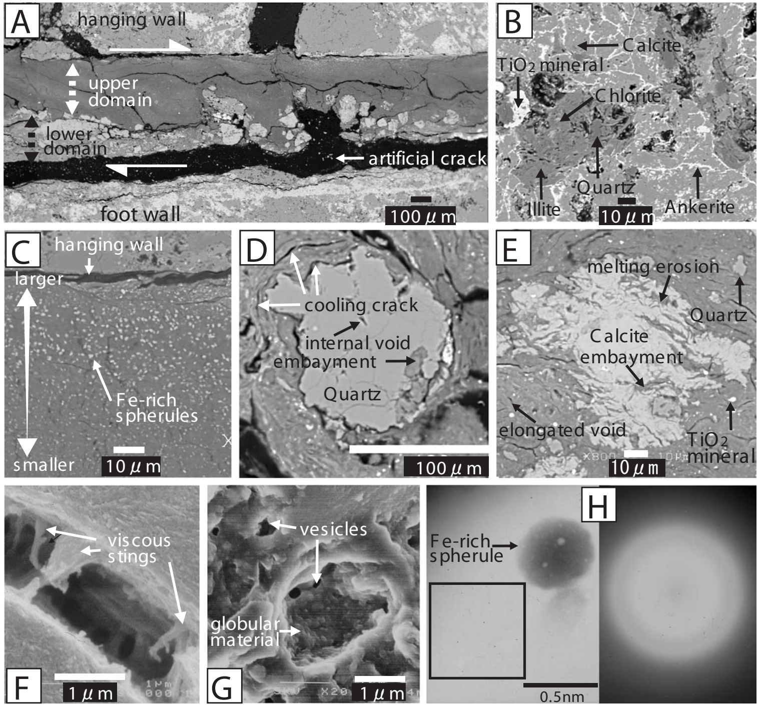

Fig. 4. SEM and TEM images for the pseudotachylyte. **(A)** Upper molten domain and lower ultracataclaste-dominated domain in the fault vein. **(B)** Implosion breccia encircled by carbonate matrix. Note that Carbonates are composed of a few μm calcite and grain boundary filling ankerite. **(C)** Concentration of Fe-rich spherules along the margin. Note that size of spherule enlarges along the margin. **(D)** Embayment and cooling cracks surrounding quartz grain in the upper domain. **(E)** Embayment and cooling cracks surrounding calcite. Note embayment of calcite more marked than that of quartz. **(F)** Icicle-like viscous stings in the cooling crack. **(G)** Globular surface and vesicles associated in the elongated void. **(H)** Left: TEM bright-field image of the pseudotachylyte. Right: Electron diffraction pattern in the box of the left documenting amorphous material.